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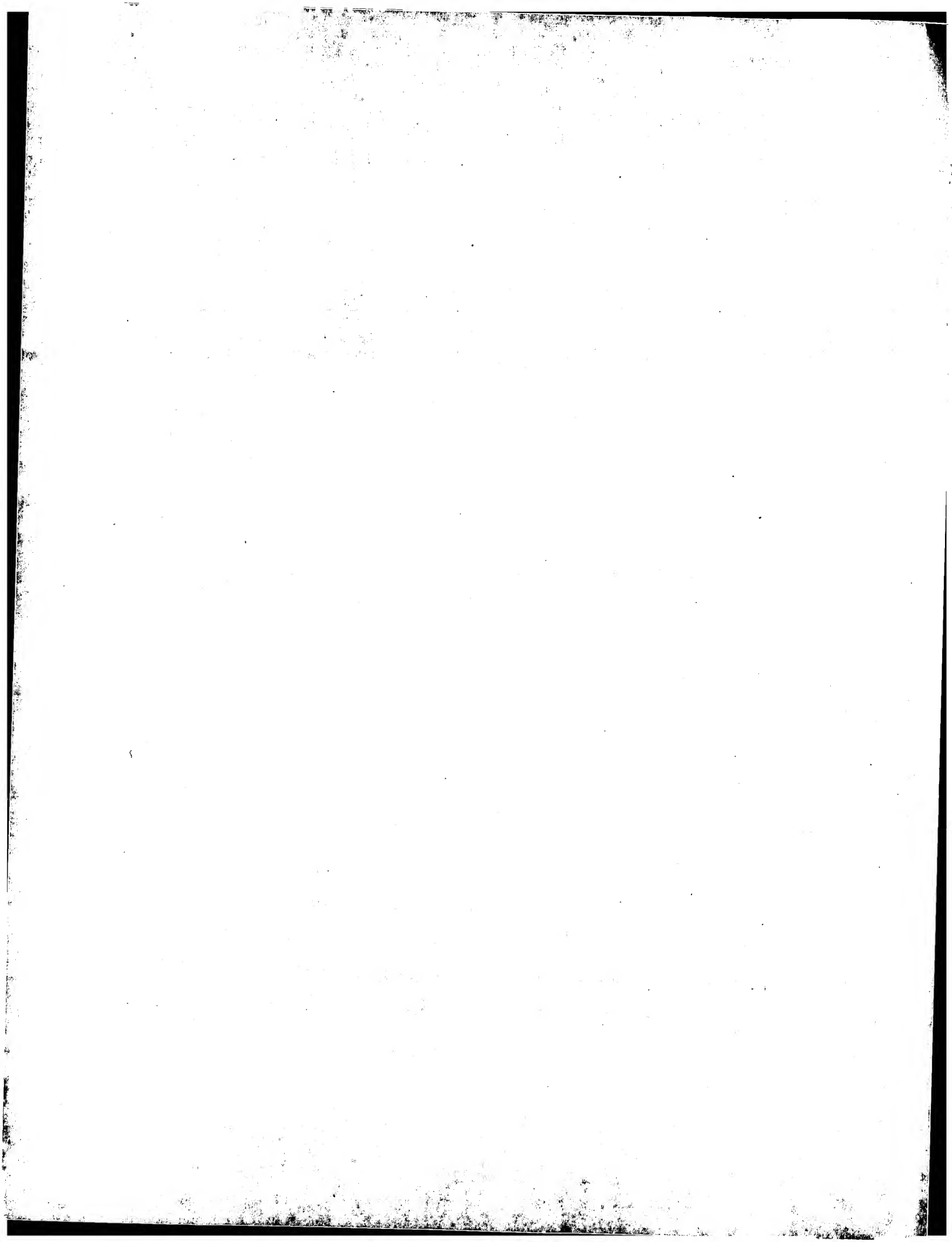
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(54) Adaptive compensating ramp generator for current-mode DC/DC converters.

(57) A circuit (20, 40, 50, 60) for generating an optimal compensating ramp voltage signal V_{cramp} , with the minimum necessary slope, m_c , for a current mode DC/DC converter is shown. The adaptive compensating ramp generating circuit (20) is comprised of two voltage dividers (22, 24), the first voltage divider 22 divides an input voltage V_{IN} and the second voltage divider 24 divides an output voltage V_{OUT} . The first voltage divider (22) has two resistors (26, 28) in series: the first resistor (26) has a resistance of $(1/B - 1) \cdot R$ ohms and the second resistor (28) has a resistance of R ohms. V_{OUT} is divided by the second voltage divider (24) having two resistors (29, 30) in series: the first resistor (29) has a resistance of $(1/A - 1) \cdot R$ ohms and the second resistor (30) has a resistance of R ohms. The constants A , B , and C are selected for the particular type of DC/DC converter employed. The divided voltages $A \cdot V_{\text{OUT}}$ and $B \cdot V_{\text{IN}}$ are input into a voltage controlled current source (32). The voltage controlled current source (32) has a scaling resistor R_{scale} , an amplifier (36), a transistor Q , and a diode $D1$. The output of the current source (38) is coupled to a capacitor C_{ramp} whose voltage realizes the slope of the compensating ramp signal, V_{cramp} . The capacitor C_{ramp} is charged through R_{scale} .

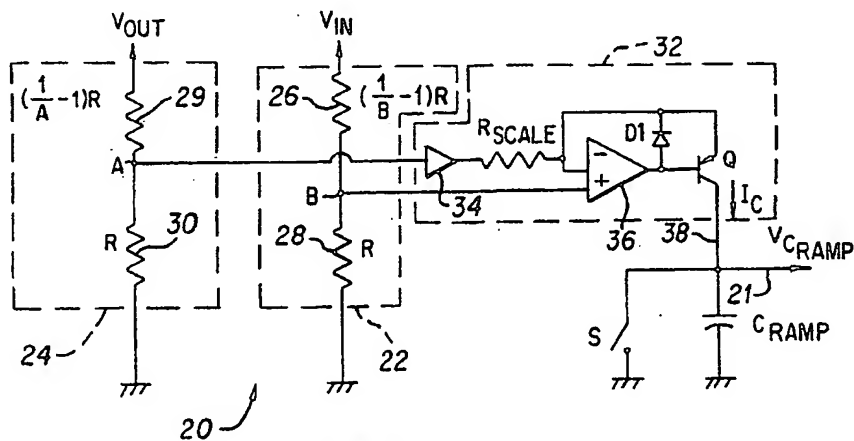


FIG. 4

The present invention relates to a compensating ramp and more particularly the invention relates to an adaptive compensating ramp generator for current mode DC to DC converters.

A compensating ramp changes the slope at which a reference voltage intersects with the current sense voltage signal. Conventional current-mode controlled DC to DC (DC/DC) converters operating above 50% duty cycle need a compensating ramp signal superimposed on a current sense signal, which is used as a control parameter, to avoid "open loop instability" or "subharmonic oscillation".

To avoid subharmonic oscillation, the slope of the current sense voltage during ON time (m_{up}) must be greater than the reflected slope (m_{do}), where the reflected slope is the change between the ending amplitude of the current sense voltage and its starting amplitude at the beginning of the next cycle, divided by the OFF time. m_{up} is usually less than m_{do} for a >50% duty cycle. Therefore, to make m_{up} greater than m_{do} , a ramp signal having additional slope is superimposed onto the current sense signal.

In the past, the compensating ramp signal was formed by scaling the system's oscillator timing signal and adding it to the current sense voltage or deducting it from the error amplifier's output voltage. The necessary slope of the compensating ramp signal is dependent upon the input and output voltage of the DC/DC converter and the value of the inductor used. In transformer coupled systems, the necessary slope is also dependent upon the transformer's turn ratio.

Traditional systems set the ramp signal's slope to accommodate for the worst case conditions: maximum output voltage (in variable output voltage systems only) and minimum input voltage. By designing the slope to accommodate for the worst case situation, under normal operating conditions, the slope and accordingly the amplitude of the ramp is higher than necessary. For example, in wide input range systems, the amplitude is often two to three times higher than necessary for stability.

There are two primary disadvantages associated with having a compensating ramp signal with excessive slope. First, the maximum available output current of the system is limited; the steeper the slope, the lower the amount of current available at current limit. Second, the phase margin of the amplitude control loop is decreased.

The independent claims define the concept of the present invention aiming to overcome the drawbacks set forth above.

Preferably, the present invention provides a circuit for generating a compensating ramp signal in a switching regulator of the type which is responsive to an unregulated input voltage (V_{in}) and which provides a regulated output voltage (V_{out}). The circuit includes a sense resistor (R_s) which provides a signal proportional to the current flowing through the switch; means for storing energy having an inductance (L); and means for amplifying having a predetermined gain (A_1) to amplify the signal from the sense resistor. The signal from the sense resistor is used to control the operation of the switching regulator.

The compensating ramp circuit comprises means for generating a compensating ramp voltage signal having a slope (m_c) which conforms to the equation $m_c > (A * V_{out} - B * V_{in}) * C$ where $A \leq 1$, $B \leq 1$, and C is a constant dependent upon R_s , L , and magnetic coupling parameters associated with the energy storage means. The circuit includes means for superimposing the generated compensating ramp voltage onto the signal from the sense resistor such that the stability of the switching regulator is ensured.

Parameters A, B, C are selected according to the type of switching regulator. The means for generating the compensating ramp having the slope m_c , in the preferred embodiment, may include means responsive to the output voltage for providing a first signal which is equal to the output voltage divided by a first preselected amount, means responsive to the input voltage for providing a second signal which is equal to the input voltage divided by a second preselected amount, and means for generating a signal proportional to the difference between the first and second signals.

According to the present invention it is possible to optimize the amplitude and slope of a compensating ramp signal to have the maximum available current available at current limit.

In preferred form, the present invention is to provide an adaptive compensating ramp generator having one external scaling resistor to generate the necessary ramp over the entire input/output voltage range of a DC/DC converter and frequency range, in adjustable frequency systems.

Preferably, the present invention employs an internal fixed scaling resistor in a fixed frequency system with a limited range of applicable inductors.

These, and further objects and advantages of the present invention will be made clear or will become apparent during the course of the following description of the preferred embodiment of the present invention.

In the accompanying drawings:

Figure 1 is a functional block diagram of a conventional buck DC to DC converter having a compensating

ramp generator;

Figure 2 is a timing diagram corresponding to the circuit of Figure 1;

Figure 3 is a diagram of the buck converter of Figure 1 having a traditional fixed slope compensating ramp generator circuit.

5 Figure 4 is a circuit diagram of a ramp generator circuit of the present invention;

Figure 5 is circuit diagram of another ramp generator of the present invention for a DC/DC boost converter;

Figure 6 is a circuit diagram of another ramp generator of the present invention for a DC/DC buck converter;

10 Figure 7 is a block diagram of a DC/DC flyback converter having a ramp generator of the present invention;

Figure 8 is a block diagram of a DC/DC buck-boost converter having a ramp generator of the present invention;

Figure 9 is a block diagram of a DC/DC forward converter having a ramp generator of the present invention; and

15 Figure 10 is a circuit diagram of still another ramp generator of the present invention.

Referring to Figures 1 and 2, Figure 1 is a functional block diagram of a current mode buck (or step down) DC to DC (DC/DC) converter 10 operating at above a 50% duty cycle and having a compensating ramp generator 12. Figure 2 is the timing diagram corresponding to the circuit 10 in Figure 1. Figure 2c
20 illustrates the slope m_{up} and the reflected slope m_{do} of the current sense signal through R_s having voltage V_s . A DC/DC converter converts one signal having a particular DC level to another DC level. The buck converter 10 includes a power switch 14 which may be a field effect transistor (FET); a sense resistor R_s connected between an input voltage source V_{in} and the power switch 14; a ramp scaling resistor R_r connected between the resistor R_s and the switch 14 where Voltage V_c is the voltage drop across R_r and V_c
25 has a slope of m_c ; a current amplifier A_1 which has V_{in} and voltage V_c as its inputs; and filtering components 16 which are connected between the power switch 14 and a load R_L . The filtering components 16 include a capacitor C_o , an inductor L , and a diode D . The output voltage V_{OUT} is provided at one of the inputs to an error amplifier 11. The error amplifier 11 is comprised of an amplifier A_e which compares V_{OUT} with a reference voltage V_{ref} .

30 The current through the power switch 14 I_{14} (Figure 2b) is sensed by resistor R_s . The sensed current is used to turn the power switch 14 OFF. Resistor R_r scales the compensating ramp voltage V_c having a slope of m_c , and is much greater than sense resistor R_s ($R_r \gg R_s$).

The system clock 18 or oscillator provides a clock pulse V_s (Figure 2a) to the main flip-flop FF 40 and turns on the switch 14 in each period. As illustrated in Figures 2a, 2b and 2c, the clock pulse V_s turns on
35 the switch 14 causing current to flow through the switch I_{14} and resistor R_s . The voltage V_s wave form and power current waveform mirror one another.

The compensating ramp generator 12 also receives the system clock 18 timing signal, V_{osc} , and voltages V_{in} and V_{OUT} . The compensating ramp generator 12 generates a compensating ramp signal 21 having a voltage V_{cramp} (Figure 2d) and a slope of

40

$$m_{21} = \frac{m_c}{g_m * R_r}$$

45 where g_m is the transconductance of a voltage to current converter 42. V_{TH} , a threshold voltage, adjusts the starting instant of the ramp signal 21 and the voltage to current converter 42 level shifts the compensating ramp signal 21 up to the voltage level of the input signal V_{in} and generates a level shifted compensating ramp signal 43.

The voltage of the level shifted compensating ramp signal 43 is V_c . V_c is the voltage drop across the ramp scaling resistor R_r . The compensating ramp generator 12 may also use V_{in} , V_{OUT} , V_{osc} , the output
50 signal of the flip-flop 40 and a DC threshold voltage V_{th} to generate the compensating ramp signal 21, depending on the construction of the compensating ramp generator circuit 12 employed.

The output signal 15 of the error amplifier 11 is input to a comparator 13 where it is compared with the amplified signal 23. (Figure 2g). The amplified signal 23 is the amplified sum $V_c + V_s$ of the switch current
55 sense voltage V_s and V_c (Figure 2f). When the modified current sense signal 23 is equivalent to the output signal 15 out of the error amplifier 11, comparator 13 outputs a comparison signal 17 (Figure 2h) when the current sense signal 23 is equivalent to the output signal 15. The comparison signal 17 is input to flip flop 40 and resets the flip-flop 40.

The flip flop 40 outputs a driver control signal 40 (Figure 2i) which turns off the switch 16 through driver 19. Referring in particular to Figures 2h and 2i, when the comparison signal 17 is high, the signal 41 out of the flip flop 41 goes low and the switch 14 is turned OFF. The flip flop output signal 41 remains low until the next clock pulse V_s is received. The maximum available output voltage of the error amplifier 11 thereby limits the available maximum current from the switch 14 (i.e., the maximum available voltage limit acts as a current limit). In most systems, the error amplifier's maximum output voltage is internally limited to set the current limit to the desired value.

The condition for stability of a conventional DC/DC converter's power stage is:

$$m_c \geq m_{do} - m_{up} \quad / 1 /$$

where

m_c = slope of the level shifted compensating ramp voltage signal V_c

m_{up} = slope of the current sense voltages V_s during ON-time

m_{do} = reflected slope (i.e., the change in amplitude between the ending amplitude of the current sense voltage during an ON-time cycle and the starting amplitude of the current sense voltage at the beginning of the next ON-time cycle, divided by the OFF time.)

For a buck DC/DC current-mode converter the slopes of m_{up} and m_{do} of Equation (Eq.) 1 are defined as follows:

$$m_{up} = \frac{V_{IN} - V_{OUT} - V_{SAT}}{L} * R_s \quad / 2 /$$

and

$$m_{do} = \frac{V_{OUT} + V_D}{L} * R_s \quad / 3 /$$

where V_{SAT} is the power FET saturation voltage, and V_D is the forward biased diode voltage.

Using Eq. 1, the condition for stability of the compensating ramp's slope is:

$$m_c \geq m_{do} - m_{up} = \frac{2R_s}{L} \left[V_{OUT} - \frac{V_{IN}}{2} + \frac{V_D + V_{SAT}}{2} \right] \quad / 4 /$$

In systems with high efficiency, V_D and V_{SAT} are $\ll V_{OUT}$ and $\ll V_{IN}$, and therefore, V_D and V_{SAT} can be neglected. Therefore, m_c becomes:

$$m_c > (A * V_{OUT} - B * V_{IN}) * C \quad / 5 /$$

where

$$A \leq 1$$

$$B \leq 1$$

C = a constant which is dependent upon the R_s , L , n ($n = n_s/n_p$ the turns ratio of any transformer employed) and L_p (primary inductance of any transformer employed in the switching circuit.)

The minimum necessary slope of the level shifted compensating ramp signal 43 (Figure 1), for most types of current-mode-controlled DC/DC converters, can be expressed in the format of Equation 5. In particular, for a buck converter, a boost converter, a flyback converter, a forward converter, and a buck-boost converter, the preferred parameters for Equation 5 are summarized below:

TABLE 1

DC/DC Converter		A	B	C
Buck		1	≤ 5	$2R_s/L$
Boost		≥ 5	1	$2R_s/L$
Flyback	$n \geq 1$	$\geq 1/n$	1	R_s/L_p
	$n < 1$	1	$\leq n$	R_s/nL_p
Forward	$n \geq 2$	$\geq 2/n$	1	$n^2 R_s/L$
	$n < 2$	1	$\leq n/2$	$2n R_s/L$
Buck-Boost		1	≤ 1	R_s/L

The compensating ramp slope m_c is meaningful only if it is positive or 0.

Referring to Figure 3, a buck converter circuit 31 with a traditional compensating ramp generator circuit 33 is illustrated. Elements in other embodiment which are similar are referred to with the same reference numerals/names. The transistor Q12 and resistor R_{scale} realize the compensating ramp block 12 and the V to I converter block 42 in Figure 1. In the circuit 31 R_f/R_{scale} and the slope of the oscillator's timing signal (V_{cosc}) set the slope of the compensating ramp voltage V_c having a slope m_c . Aside from the disadvantage of generating a compensating ramp voltage V_c having a fixed slope, the circuit 31 has high temperature sensitivity because of the approximately $-0.3\%/^\circ K$ temperature coefficient of the base-emitter voltage of transistor Q12.

Referring to Figure 4 in conjunction with Table 1, an adaptive circuit 20 for generating a compensating ramp voltage signal (V_{cramp}), having a minimum slope, m_{21} , where

$$m_{21} = \frac{m_c}{g_m * R_r}$$

for most types of DC/DC converters, is illustrated. The circuit 20 generates the optimal compensating ramp signal 21 with the minimum slope m_{21} , for a specific type of DC/DC converter by selecting the constants A, B, and C according to Table 1. A and B may be varied so long as A and B are selected so that m_c is larger or equivalent than necessary (i.e., to ensure the stability of the system). C may also be varied to be greater than the value in Table 1. But, the farther A and B deviate from the preferred values of Table 1, the higher the ramp generated and the less current available at current limit because the error amplifier's maximum output voltage is constant.

The adaptive compensating ramp generating circuit 20 is comprised of two voltage dividers 22, 24. The first voltage divider 22 divides an input voltage V_{IN} and the second voltage divider 24 divides an output voltage V_{OUT} . For a boost converter, for example, $V_{IN} \leq V_{OUT}$ and for a buck converter, $V_{IN} \geq V_{OUT}$.

The input voltage, V_{IN} , is divided by the first voltage divider 22 having two 26, 28 resistors in series: the first resistor 26 has a resistance of $(1/B - 1) * R$ ohms and the second resistor 28 has a resistance of R ohms such that the divided voltage at point B is $V_{IN} * B$. Output voltage, V_{OUT} , is divided by the second voltage divider 24 having two resistors 29, 30 in series: the first resistor 29 has a resistance of $(1/A - 1) * R$ ohms and the second resistor 30 has a resistance of R ohms such that the divided voltage at point A is $V_{OUT} * A$. The divided voltages $A * V_{OUT}$ and $B * V_{IN}$ serve as the two inputs to a voltage controlled current source 32 which has two inputs and an output 38.

The voltage controlled current source 32 includes a buffer amplifier 34 connected to a scaling resistor R_{scale} and a feedback loop operational amplifier 36 which is connected between the scaling resistor R_{scale} and a transistor Q, and a diode D1. Since the operational amplifier 36 is a feedback loop amplifier, ideally, it does not consume current, so that the current across the scaling resistor R_{scale} is:

$$I_{RSCALE} = \frac{A * V_{OUT} - B * V_{IN}}{R_{scale}} \quad / \quad 6 \quad /$$

The output of the current source 38 is coupled to a capacitor C_{ramp} whose voltage realizes the slope m_{21} of the compensating ramp signal, V_{cramp} . The capacitor C_{ramp} is charged through the I_c collector current of the Q transistor. If the transistor Q has a reasonably high β , $I_c = I_E = I_{\text{RScale}}$ (for example, a β of about 100 or higher). Resistor R_{Scale} controls the rate at which the voltage increases in the capacitor C_{ramp} (i.e. the rate at which the capacitor charges up). The slope of the compensating ramp signal 21 having the voltage V_{cramp} is:

$$m_{21} = \frac{I}{C_{\text{ramp}}} = \frac{A V_{\text{OUT}} - B V_{\text{IN}}}{R_{\text{Scale}} * C_{\text{ramp}}} = \frac{1}{R_{\text{Scale}} C_{\text{ramp}}} (A * V_{\text{OUT}} - B * V_{\text{IN}}) \quad / \quad 7 \quad /$$

where the constant C in Equation 5 is:

$$C = \frac{1}{R_{\text{Scale}} * C_{\text{ramp}}} g_m R_r$$

A switch S across the capacitor C_{ramp} discharges capacitor C_{ramp} at the end of each period. The switch S is ON until the start of the next clock period (when the main switch 14 turns ON again) or almost until half of the next clock period has elapsed.

The value of the capacitor C_{ramp} , the resistor R_{Scale} , R_r and g_m , realize the necessary value of the constant C in Eq. 5.

The C constant of Eq. 7 has to be more than equal to the C constant of the converter according to Table 1. For example, for a boost converter,

$$\frac{g_m R_r}{R_{\text{Scale}} * C_{\text{ramp}}} > \frac{2R_s}{L} \quad / \quad 8 \quad /$$

$$\text{Therefore, } R_{\text{Scale}} < \frac{L * g_m R_r}{C_{\text{ramp}} * 2R_s}$$

Referring to Figure 5 and to Table 1, for a DC/DC converter either A or B is 1. Hence, the circuit 20 may be simplified by eliminating the buffer amplifier 34 and the operational amplifier 36 and replacing the amplifier 36 by a single transistor Q2. A compensating ramp generator circuit 40 for a boost converter is illustrated in Figure 5. The boost ramp generator circuit 40 is based upon the modified general compensating ramp generator circuit 20 of Figure 4, the general circuit 20 having been modified and simplified to reflect the preferred values of A, B, and C for the boost converter.

In the preferred embodiment, for a boost converter circuit 40, A is about equal to 0.5, B is about equal to 1, and C is about equal to $2 R_s/L$. The boost converter ramp generator circuit 40 has a voltage controlled current source 42 which is comprised of two bipolar transistors Q1, Q2. Transistor Q1 is responsive to the output voltage V_{OUT} and transistor Q2 is responsive to the input voltage V_{IN} . In the preferred embodiment, transistor Q1 is a PNP transistor which is used as an emitter follower. Transistor Q1's base is connected to a first voltage divider 44 having a first resistor R_1 having a resistance of R ohms, in series with a second resistor R_2 having a resistance of R ohms such that the divided voltage at point A is $0.5 V_{\text{OUT}}$.

Transistor Q1's emitter is biased to a first potential V_{OUT} through a resistor R_3 , with a resistance of R ohms, to ensure that transistor Q1 operates in the linear active region. Transistor Q1's collector is connected to ground.

The second transistor Q2 is a split collector PNP transistor, in the preferred embodiment. Two transistors having their bases and emitters connected together may be used instead of the split collector PNP transistor. The circuit 40 is responsive to the change in current through transistor Q2's multiple collectors C1, C2. Transistor Q2's emitter is connected to transistor Q1's emitter such that transistor Q2's base voltage is also $0.5 * V_{\text{OUT}}$. One of Q2's collectors C2 is connected to its base and to a scaling resistor,

R_{scale} .

Transistor Q2 acts like a current mirror since the current I_c which flows through resistor R_{scale} is mirrored and output to the capacitor C_{ramp} . By charging and discharging C_{ramp} , by a switch, S, the compensating ramp voltage V_{oramp} is generated.

5 In a boost converter since B is about 1, the second voltage divider has a division ratio of 1 (i.e., the divider is redundant (non-existent)). Hence voltage V_{IN} is not divided down before being fed to resistor R_{scale} . Voltage V_{IN} is connected to transistor Q2 through resistor R_{scale} . The resistor R_{scale} , capacitor C_{ramp} , the split ratio between the two PNP collectors together with g_m and R_f realize the C constant of Eq. 5.

Referring now to Figure 6, a compensating ramp generating circuit for a buck converter 50 is illustrated. 10 The buck compensating ramp generator circuit 50 is functionally equivalent to the general compensating ramp circuit 20 of Figure 4, however the buck ramp circuit 50 having been designed to account for the preferred parameters identified in Table 1. As shown in Table 1, for a buck converter, A is about equal to 1, B is about equal to 0.5, and C is about equal to $2 R_{scale}/L$.

The buck converter ramp generating circuit 50 is similar to the boost converter compensating ramp circuit 40 in that the buck ramp circuit 50 also has one voltage divider 52, and two bipolar transistors Q3, 15 Q4, a capacitor C_{ramp} , and a scaling resistor R_{scale} . However, in the buck compensating ramp circuit 50 transistor Q3's emitter is connected to transistor Q4's collector and base.

The voltage divider 52 has a first resistor R_1 and a second resistor R_2 in series each having a resistance of R ohms. The first voltage divider 52 is connected to a first potential V_{IN} such that the voltage 20 at point B is $0.5 * V_{IN}$. Hence, the voltage into transistor Q3's base is $0.5 * V_{IN}$. Transistor Q3's collector is coupled to V_{IN} . Resistor R_3 has a resistance of R ohms and it ensures that transistor Q3 operates in the linear active region. Since A is about equal to 1 in a buck converter, voltage V_{OUT} is connected directly to transistor Q4 through resistor R_{scale} .

In the preferred embodiment, transistor Q4 is a split collector PNP transistor where one of its collectors 25 C2 is connected to transistor Q3's emitter and also to its base. As previously discussed, two transistors may be used instead of a split collector transistor. The other collector C1 of transistor Q4 is coupled to capacitor C_{ramp} . Transistor Q4's emitter is coupled to resistor R_{scale} and transistor Q3's emitter sets the voltage across the resistor R_{scale} and the base-emitter of transistor Q4.

Transistor Q4 acts like a diode and functions like a current splitter. It splits its emitter current, which is 30 set up by R_{scale} , V_{OUT} , and Q3's emitter voltage, into two equivalent parts: I_c' and I_c (if the split ratio of C1 and C2 is $\frac{1}{2}$ to $\frac{1}{2}$). I_c' charges the capacitor C_{ramp} . In this manner, V_{OUT} sets the current in the capacitor C_{ramp} through C1 since the current across resistor R_{scale} is split.

Referring to Figure 7 a flyback DC/DC converter circuit 70 is illustrated having a compensating ramp generator 20 of the present invention. The filtering component 16 of the flyback circuit 70 includes a 35 transformer 72. The transformer has n_p number of primary turns and n_s number of secondary turns such that $n = n_s/n_p$ (the transformer's turns ratio). In addition, the sense resistor R_{sense} is referenced to ground, the switch's 14 drain is coupled to the primary inductor, and the switch's 14 source is connected to ground through resistor R_{sense} . As shown in Table 1, in the compensating ramp generator circuit 20 for a flyback converter for $n > 1$, A is about equal to $1/n$ and B is about equal to 1; for $n < 1$, A is about equal to 1 and B 40 is about equal to n. The circuit 20 may be modified for these preferred parameters.

Referring to Figure 8, a buck boost DC/DC converter circuit 80 is illustrated having a compensating ramp generator 20 of the present invention. The buck boost circuit 80 is similar to the conventional buck converter circuit 10 illustrated in Figure 1 but in the buck boost circuit 80 the inductor and the diode change 45 places. As shown in Table 1, for the ramp generator circuit 20 for the buck boost converter, A is about equal to one, B is about equal to 1, and C is about equal to R_s/L . Again the ramp generator circuit may be modified for these preferred parameters.

Referring to Figure 9, a forward DC/DC converter circuit 90 is illustrated having a compensating ramp generator 20 of the present invention. The forward circuit 90 is similar to the Figure 7 but the filtering component 16 of the forward circuit 90 further includes an inductor, L, 94 and an additional diode D3 in 50 addition to the transformer 92. In the forward circuit 90, the sense resistor R_{sense} is referenced to ground, and the power switch 14 drain is coupled to the transformer 92. The switch's 14 source is also referenced to ground through resistor R_{sense} . The transformer 92 has a turns ratio of $n = n_s/n_p$. As shown in Table 1, for the compensating ramp generator circuit 20 for the forward DC/DC converter for $n > 2$: A is about equal to $2/n$, B is about equal to 1, and C is about equal to $n^2 R_s/L$. For $n < 2$, A is about equal to 1, B is about equal 55 to $n/2$, and C is about equal to $2*n*R_s/L$.

Referring to Figure 10, another circuit diagram of a compensating ramp generator circuit 60 having a multiplier 62 and a constant slope ramp voltage signal 68, is illustrated. The constant slope ramp voltage signal 68 is generated by an oscillator 18, which is present in the switching regulator circuit 10, in

conjunction with an energy storage timing element, which in the preferred embodiment is a capacitor C_{osc} .

The multiplier 62, which is a differential input multiplier in the preferred embodiment, has two differential input pairs (x1, x2) and (y1, y2) and an output voltage V_{cramp} . Input y1 corresponds to the constant slope ramp voltage signal 65. The gain coefficient D of the multiplier 62 is

$$D = \frac{C}{m_{osc} * g_m * R_r}$$

10 where

m_{osc} = is the slope of the constant slope voltage signal 68 of the energy storage timing element.

C = is the C constant of Eq. 5

The first pair of multiplier inputs (x1,x2) is connected to a first and a second voltage divider, 64, 66 respectively. The first voltage divider 64, for dividing a first potential V_{OUT} , and has two resistors $(1/A - 1) * R$ and R_1 in series. The divided voltage V_{OUT} at point A is denoted as x2.

15 The second voltage divider 66, has two resistors $(1/B - 1) * R$ and R_2 , for dividing a second potential V_{IN} . Resistors R_1 and R_2 have substantially the same resistance of R ohms. The divided voltage V_{IN} , at point B, is denoted as x1.

One of the second multiplier inputs y1 is connected to the switching regulator circuit 10 oscillator 18 and to the capacitor C_{osc} . As previously discussed, C_{osc} , generates the constant ramp voltage V_{osc} 68. The other one of the multiplier's second input pairs y2 is connected to a DC reference voltage V_{ref} which generates a threshold voltage V_{th} . With voltage V_{th} , the starting instant of the compensating ramp can be adjusted. The value of V_{ref} is less than or substantially the same as the average value of the ramp voltage out of the multiplier V_{cramp} .

25 Resistor R_{scale} is the gain setting resistor of the multiplier 62 that sets the C constant to the appropriate value. The multiplier 62 takes the difference between the (x1, x2) inputs and the difference between the (y1, y2) inputs and multiplies the differences by the multiplier gain coefficient D to generate a compensating ramp signal V_{cramp} .

The multiplier 62 operates only when both differential input voltages (x1, x2) (y1, y2) are positive. Otherwise voltage V_{cramp} is approximately 0. Voltage V_{cramp} is about zero if the differential voltage of either of the input pairs (x1,x2) (y1,y2) is negative.

No compensating ramp is needed when the duty cycle $d \leq 0.5$. This means that V_{th} can be set to threshold voltage $V_{th} \leq (V_p - V_v)/2$ or lower. V_p = peak value of the voltage and V_v is the minimum value of the voltage.

35 Having thus described the invention, it is recognized that those skilled in the art many make various modifications or additions to the preferred embodiment chosen to illustrate the invention without departing from the spirit and scope of the present contribution to the art. Accordingly, it is to be understood that the prosecution sought and to be afforded hereby should be deemed to extend to the subject matter claimed and all equivalents thereof within the scope of the invention.

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Claims

1. A circuit for generating a compensating ramp in a switching regulator of the type which is responsive to an unregulated input voltage (V_{IN}) and which provides a regulated output voltage (V_{OUT}), having a controlled switching element further having a sense resistor (R_s) which provides a signal proportional to the current flowing through the switching element, the signal being used to control the operation of the switching regulator, and means for storing energy having an inductance (L), the compensating ramp circuit comprising:

50 means for generating a compensating ramp voltage having a slope (m_c) which conforms to the equation $m_c \geq (A * V_o - B * V_{IN}) * C$

where

$A \leq 1$

$B \leq 1$

55 C is a constant dependent upon R_s , L and magnetic coupling parameters associated with the energy storage means; and

means for superimposing the generated compensating ramp voltage onto the signal from the sense resistor whereby the stability of the switching regulator is maintained.

2. The circuit of Claim 1, wherein A, B, C are selected according to the type of switching regulator as follows:

Switching Regulator	A	B	C
Buck	1	≤ 5	$2R_s/L$
Boost	≥ 5	1	$2R_s/L$
Buck-Boost	1	≤ 1	R_s/L

3. The circuit of Claim 1, wherein the switching regulator is a buck converter and A is equal to about one, B is equal to about one-half, and C is equal to about $2^*R_s/L$.

4. The circuit of Claim 1, wherein the switching regulator is a boost converter and A is about equal to one-half, B is about equal to one, and C is about equal to $2^*R_s/L$.

5. The circuit of Claim 1, wherein the means for storing energy is a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n, where $n = n_s/n_p$, and the inductance of the energy storing means is L_p .

6. The circuit of Claim 5, wherein A, B, and C are selected according to the type of switching regulator as follows:

Switching Regulator		A	B	C
Flyback	$n > 1$ $n < 1$	$\geq 1/n$ 1	1 $\leq n$	R_s/L_p R_s/nL_p
Forward	$n > 2$ $n < 2$	$\geq 2/n$ 1	1 $\leq n/2$	n^2R_s/L $2nR_s/L$

7. The circuit of Claim 5, wherein the switching regulator is a flyback converter and n is greater than about one such that A is about equal to $1/n$, B is about equal to one, and C is about equal to R_s/L_p .

8. The circuit of Claim 5, wherein the switching regulator is a flyback converter and n is less than about one such that A is about equal to one, B is about equal to n, and C is about equal to $R_s/(n^*L_p)$.

9. The circuit of Claim 5, wherein the switching regulator is a forward converter and n is greater than about two such that A is about equal to $2/n$, B is about equal to 1, and C is about equal to n^2R_s/L .

10. The circuit of Claim 5, wherein the switching regulator is a forward converter and n is less than about two such that A is about equal to one, B is about equal to $n/2$, and C is about equal to $2^*n^*R_s/L$.

11. The circuit of Claim 1, wherein the switching regulator is a buck-boost converter and A is about equal to one, B is about equal to one, and C is about equal to R_s/L .

12. A method for generating a compensating ramp signal having a slope (m_c) in a switching regulator of the type which is responsive to an unregulated input voltage (V_{IN}) and which provides a regulated output voltage (V_{OUT}), having a sense resistor (R_s) which provides a signal proportional to the current flowing through a controlled switching element, the signal being used to control the operation of the switching regulator, and means for storing energy having an inductance (L), comprising the steps of:

(A). generating a first voltage proportional to the output voltage;

(B). generating a second voltage proportional to the input voltage, wherein the proportion for the first voltage and the proportion for the second voltage are selected based upon the type of switching circuit;

(C). taking the difference between the first and second voltages and multiplying the difference by a factor determined by R_s , L and magnetic coupling parameters associated with the energy storage means to generate the compensating ramp voltage with a slope that is about equal to the multiplied difference; and

(D). superimposing the generated compensating ramp voltage onto the signal from the sense resistor whereby the stability of the switching regulator is enhanced.

13. The method of Claim 12, wherein the switching regulator is a buck converter and, the first voltage generating step in step A includes setting the first voltage so that it is about equal to the input voltage, the second voltage generating step in step B includes setting the second voltage in step B so that it is about half the output voltage, and step C includes the step of setting the factor so that it is equal to about $2^*R_s/L$.

14. The method of Claim 12, wherein the switching regulator is a boost converter and, the first voltage generating step in step A includes setting the first voltage so that it is about equal to one-half, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to $2 \cdot R_s/L$.

5 15. The method of Claim 12, wherein the means for storing energy is a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the inductance of the energy storing means is L_p , the switching regulator is a flyback converter where n is greater than about one, and the first voltage generating step in step A includes setting the first voltage so that it is about equal to $1/n$, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to R_s/L_p .

10 16. The method of Claim 12, wherein the means for storing energy is a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where

$$15 \quad n = n_s/n_p,$$

the inductance of the energy storing means is L_p , the switching regulator is a flyback converter where n is less than about one, and the first voltage generating step in step A includes setting the first voltage so that it is about equal to one, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to n , and step C includes the step of setting the factor so that it is about equal to $R_s/(n \cdot L_p)$.

17. The method of Claim 12, wherein the means for storing energy is an inductor connected to the switching element via a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the switching regulator is a forward converter where n is greater than about two, and the first voltage generating step in step A includes setting the first voltage so that it is about equal to $2/n$, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to $n^2 \cdot R_s/L$.

18. The method of Claim 12, wherein the means for storing energy is an inductor connected to the switching means via a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the switching regulator is a forward converter where n is less than about two and the first voltage generating step in step A includes setting the first voltage so that it is about equal to one, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to $n/2$, and step C includes the step of setting the factor so that it is about equal to $2 \cdot n \cdot R_s/L$.

19. The method of Claim 12, wherein the switching regulator is a buck-boost converter and the first voltage generating step in step A includes setting the first voltage so that it is about equal to one, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to R_s/L .

20. A circuit for generating a compensating ramp signal in a DC/DC converter, wherein the DC/DC converter receives an input voltage and provides an output voltage; has a sense resistor (R_s) which provides a signal proportional to the current flowing through a controlled switching element; and has means for storing energy having an inductance (L), wherein the circuit comprises:

45 means responsive to the output voltage for providing a first signal which is equal to the output voltage divided by a first preselected amount;

means responsive to the input voltage for providing a second signal which is equal to the input voltage divided by a second preselected amount;

means for generating a charging current proportional to the difference between the first and second signals; and

50 means responsive to the charging current for generating the ramp signal having a slope selected according to the particular type of DC/DC converter.

21. The circuit of Claim 20, wherein:

the first preselected amount is ≤ 1 and the second preselected amount is ≤ 1 .

22. The circuit of claim 20, wherein the means for generating the proportional charging current is a voltage controlled current source.

23. The circuit of claim 20, wherein the means responsive to the current includes a capacitive element having a value which is a function of R_s and L .

24. The circuit of claim 20 wherein the means for generating a current is comprised of:

- a first transistor means wherein the base of the first transistor means is connected to one of the means for dividing, the emitter of the first transistor means is biased to a first potential, and the collector is connected to a second potential such that the emitter base junction of the first transistor means is forward biased and the collector base junction is reverse biased; and
- 5 a second transistor means having at least two collectors wherein the first collector of the second transistor means is connected to its base, the emitter of the second transistor means is connected to the emitter of the first transistor means, and the first collector of the second transistor means is connected to the other means for dividing via a scaling resistor, and the second collector of the second transistor means provides the proportional current to the means responsive to the current for generating the ramp signal.
- 10 25. The circuit of Claim 20, wherein the means for generating a current is comprised of:
a first transistor means wherein the base of the first transistor is connected to the means for dividing which is connected to the input voltage, and the collector of the first transistor is connected to the input voltage; and
a second transistor means having at least two collectors, the first collector of the second transistor means is connected to its base and to the first transistor emitter, the emitter of the second transistor means is connected to the other means for dividing which is connected to the output voltage via a scaling resistor, the other divider is selected so that the output voltage is unchanged, and the second collector provides the proportional current to the means responsive to the current for generating the ramp signal.
- 15 26. The circuit of claim 20 wherein the means for generating a current is comprised of:
a first transistor means wherein the base of the first transistor means is connected to one of the means for dividing and the collector of the first transistor means is biased to a first potential and the emitter is biased to a second potential such that the emitter base junction of the first transistor means is forward biased;
a second transistor means having at least two collectors wherein the first collector of the second transistor means is connected to its base and to the first transistor means emitter, the emitter of the second transistor means is connected to a third potential via a scaling resistor, and the second collector of the second transistor means provides the proportional current to the means responsive to the current for generating the ramp signal.
- 20 27. The circuit of Claim 20, wherein the means for generating a current is comprised of:
a first transistor means wherein the base of the first transistor means is connected to the means for dividing which is connected to the output voltage, and the emitter of the first transistor means is connected to the output voltage via the second means for dividing; and
a second transistor means having at least two collectors, the first collector of the second transistor means is connected to its base and to the input voltage via a scaling resistor, the emitter of the second transistor means is connected to the output voltage and to the first transistor means emitter, the other divider is selected so that the input voltage is unchanged, and the second collector provides the proportional current to the means responsive to the current for generating the ramp signal.
- 25 28. The circuit of Claim 25, wherein:
the emitter of the second transistor means is connected to the output voltage through a scaling resistor.
29. The circuit of Claim 25, wherein:
the means for generating a ramp signal includes means having a capacitance which is a function of L , and R_s ; and
the ramp signal is the voltage produced across the means having a capacitance when the proportional current is used to charge the capacitance means.
30. A circuit for generating a compensating ramp voltage in a DC/DC converter, the circuit receives an input voltage and an output voltage from the converter wherein the circuit comprises:
means for dividing the output voltage by a first preselected amount;
means for dividing the input voltage by a second preselected amount;
means for generating a current proportional to the difference between the divided input voltage and the output voltage; and
- 35 50 means for multiplying the difference of the first divided input voltage and the divided output voltage with a fixed slope ramp voltage, to generate the compensating ramp signal.
31. A method for designing a compensating ramp signal having a slope (m_c) in a switching regulator of the type which is responsive to an unregulated input voltage (V_{IN}) and which provides a regulated output voltage (V_{OUT}), having a sense resistor (R_s) which provides a signal proportional to the current flowing through a controlled switching element, the signal being used to control the operation of the switching regulator, and means for storing energy having an inductance (L), comprising the steps of:
(A). generating a first voltage proportional to the output voltage;
(B). generating a second voltage proportional to the input voltage, wherein the proportion for the first

voltage and the proportion for the second voltage are selected based upon the type of switching circuit;
 (C). taking the difference between the first and second voltages and multiplying the difference by a factor determined by R_s , L and magnetic coupling parameters associated with the energy storage means to generate the compensating ramp voltage with a slope that is about equal to the multiplied difference; and
 (D). superimposing the generated compensating ramp voltage onto the signal from the sense resistor whereby the stability of the switching regulator is enhanced.

32. The method of Claim 31, wherein the switching regulator is a buck converter and, the first voltage generating step in step A includes setting the first voltage so that it is about equal to the input voltage, the second voltage generating step in step B includes setting the second voltage in step B so that it is about half the output voltage, and step C includes the step of setting the factor so that it is equal to about $2R_s/L$.

33. The method of Claim 31, wherein the switching regulator is a boost converter and, the first voltage generating step in step A includes setting the first voltage so that it is about equal to one-half, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to $2R_s/L$.

34. The method of Claim 31, wherein the means for storing energy is a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the inductance of the energy storing means is L_p , the switching regulator is a flyback converter where n is greater than about one, and the first voltage generating step in step A includes setting the first voltage so that it is about equal to $1/n$, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to R_s/L_p .

35. The method of Claim 31, wherein the means for storing energy is a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the inductance of the energy storing means is L_p , the switching regulator is a flyback converter where n is less than about one, and the first voltage generating step in step A includes setting the first voltage so that it is about equal to one, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to n , and step C includes the step of setting the factor so that it is about equal to $R_s/(nL_p)$.

36. The method of Claim 31, wherein the means for storing energy is an inductor connected to the switching element via a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the switching regulator is a forward converter where n is greater than about two, and the first voltage generating step in step A includes setting the first voltage so that it is about equal to $2/n$, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to n^2R_s/L .

37. The method of Claim 31, wherein the means for storing energy is an inductor connected to the switching means via a transformer having a primary winding of n_p turns, a secondary winding of n_s turns, and a turns ratio of n , where $n = n_s/n_p$, the switching regulator is a forward converter where n is less than about two and the first voltage generating step in step A includes setting the first voltage so that it is about equal to one, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to $n/2$, and step C includes the step of setting the factor so that it is about equal to $2nR_s/L$.

38. The method of Claim 31, wherein the switching regulator is a buck-boost converter and the first voltage generating step in step A includes setting the first voltage so that it is about equal to one, the second voltage generating step in step B includes setting the second voltage in step B so that it is about equal to one, and step C includes the step of setting the factor so that it is about equal to R_s/L .

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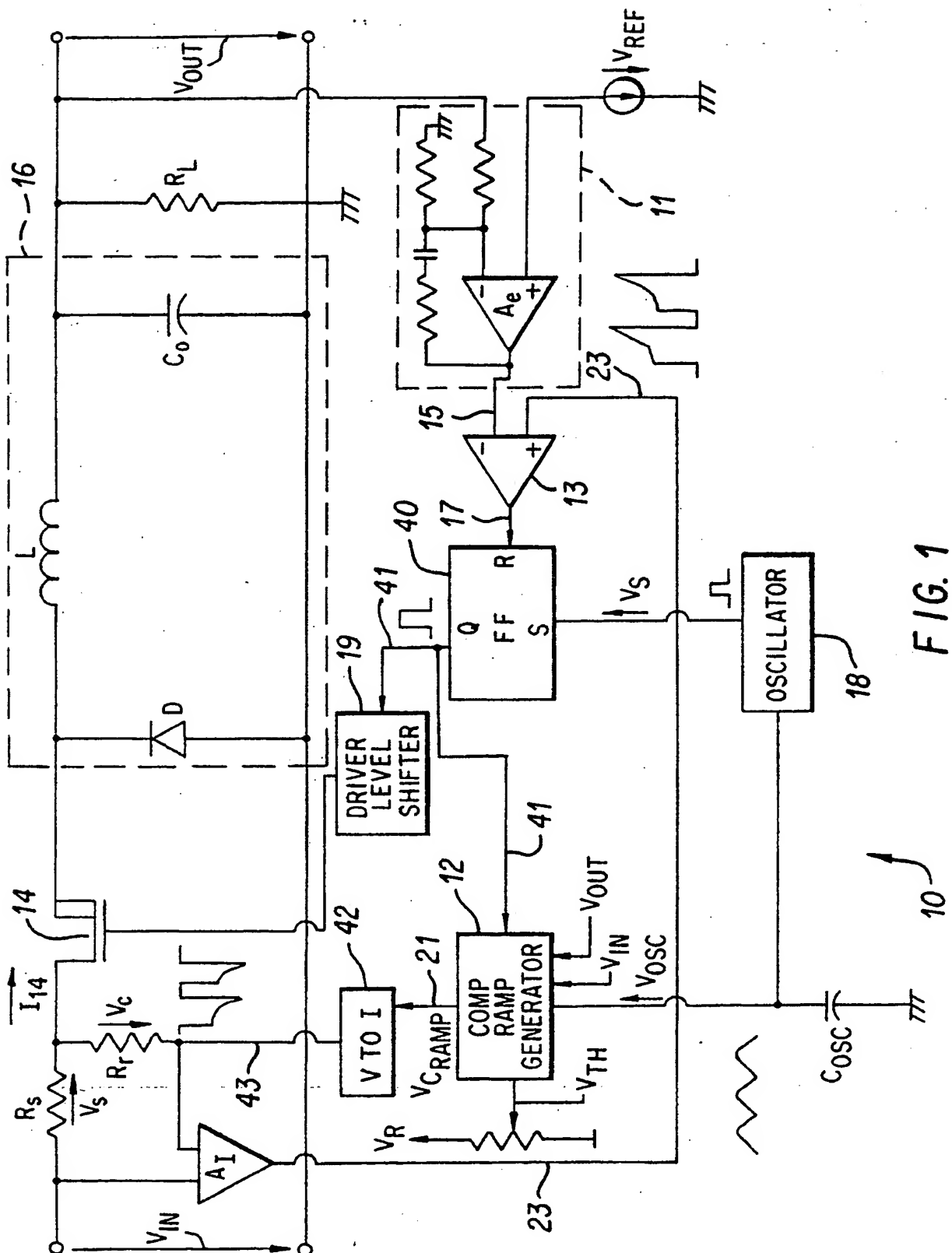
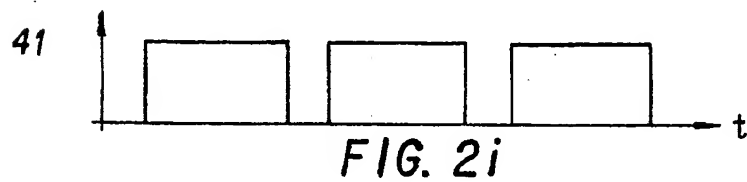
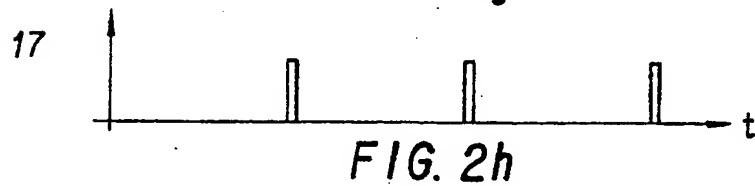
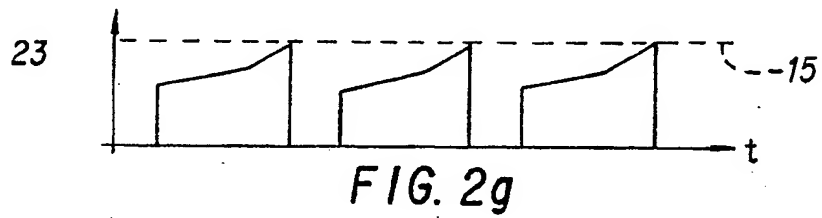
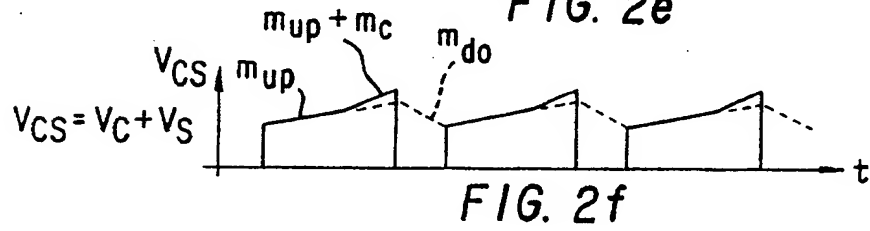
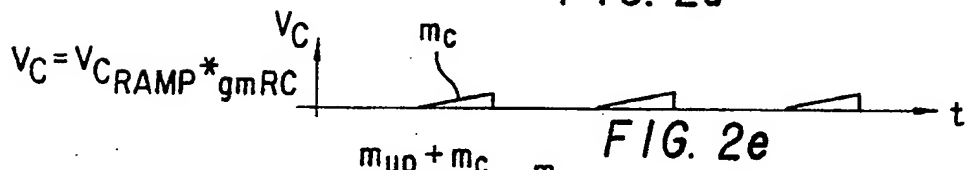
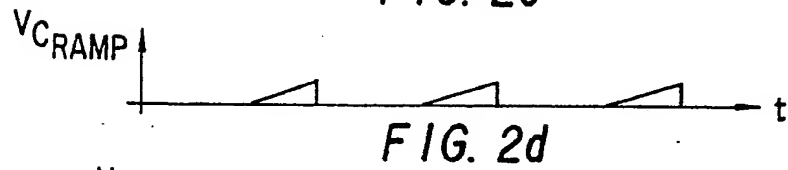
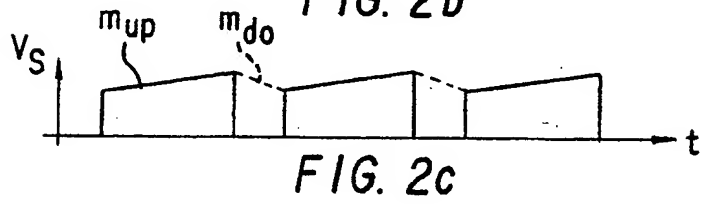
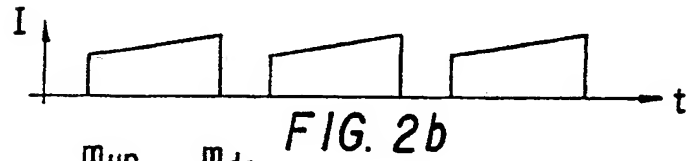
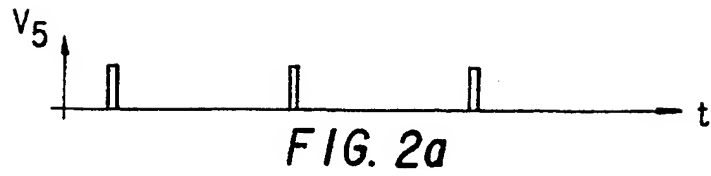


FIG. 1



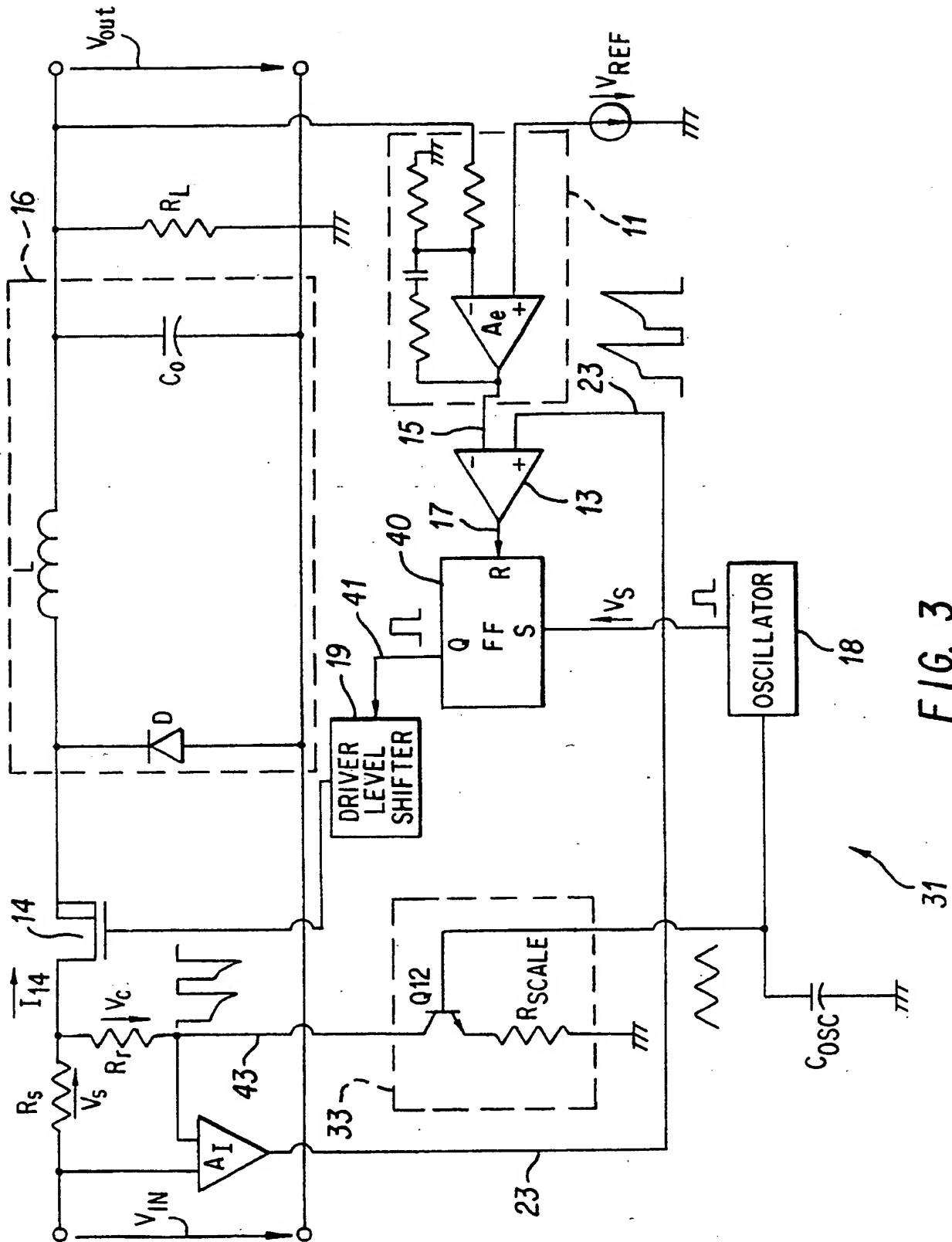


FIG. 3

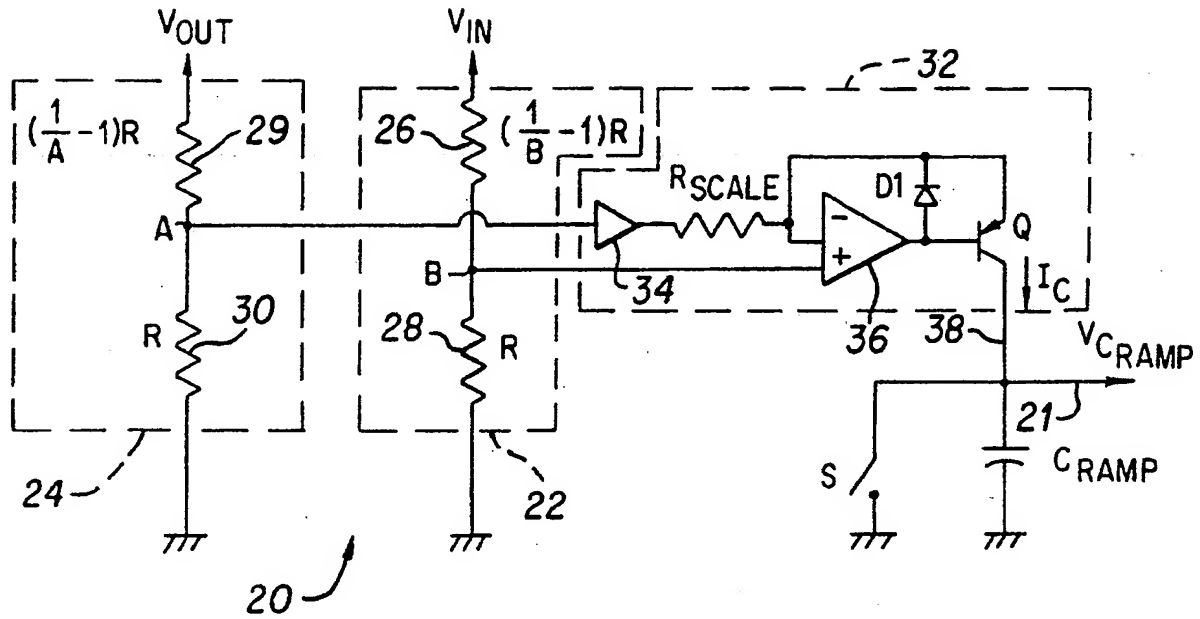


FIG. 4

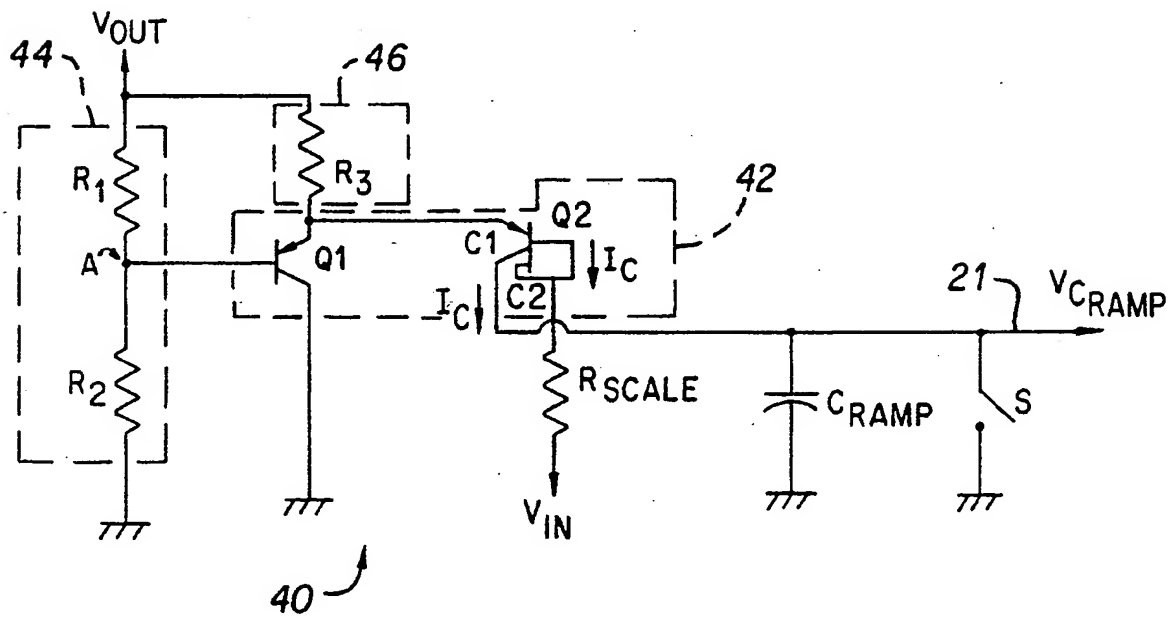
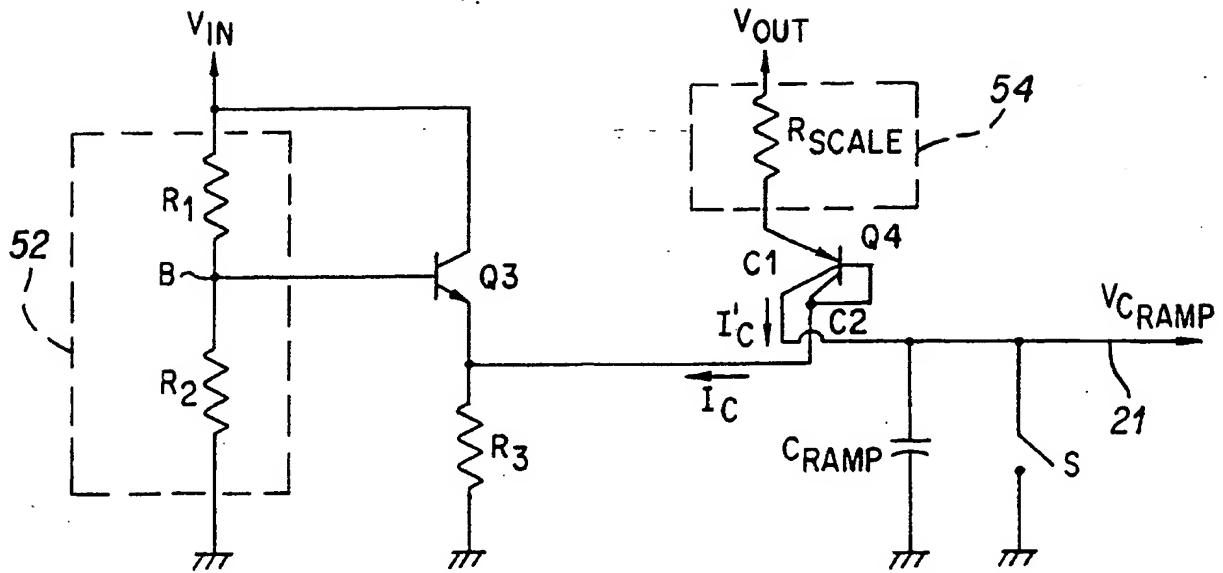


FIG. 5



50 — **FIG. 6**

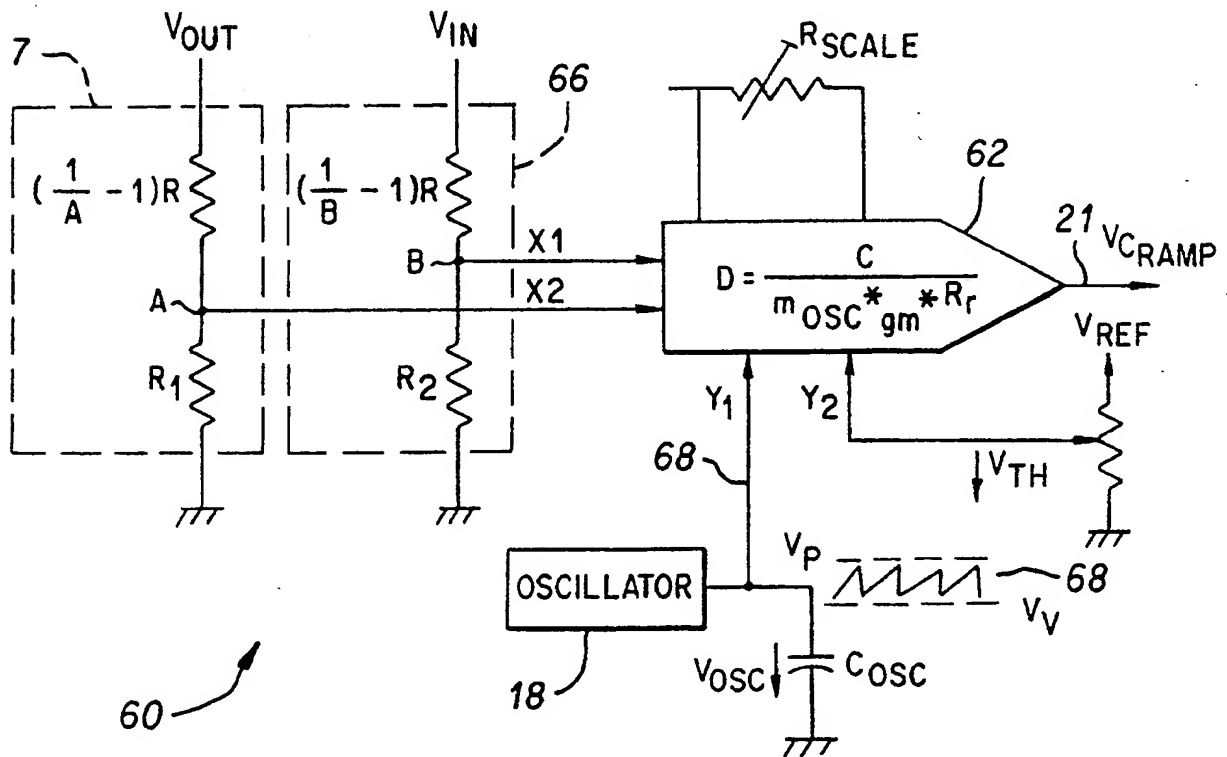


FIG. 10

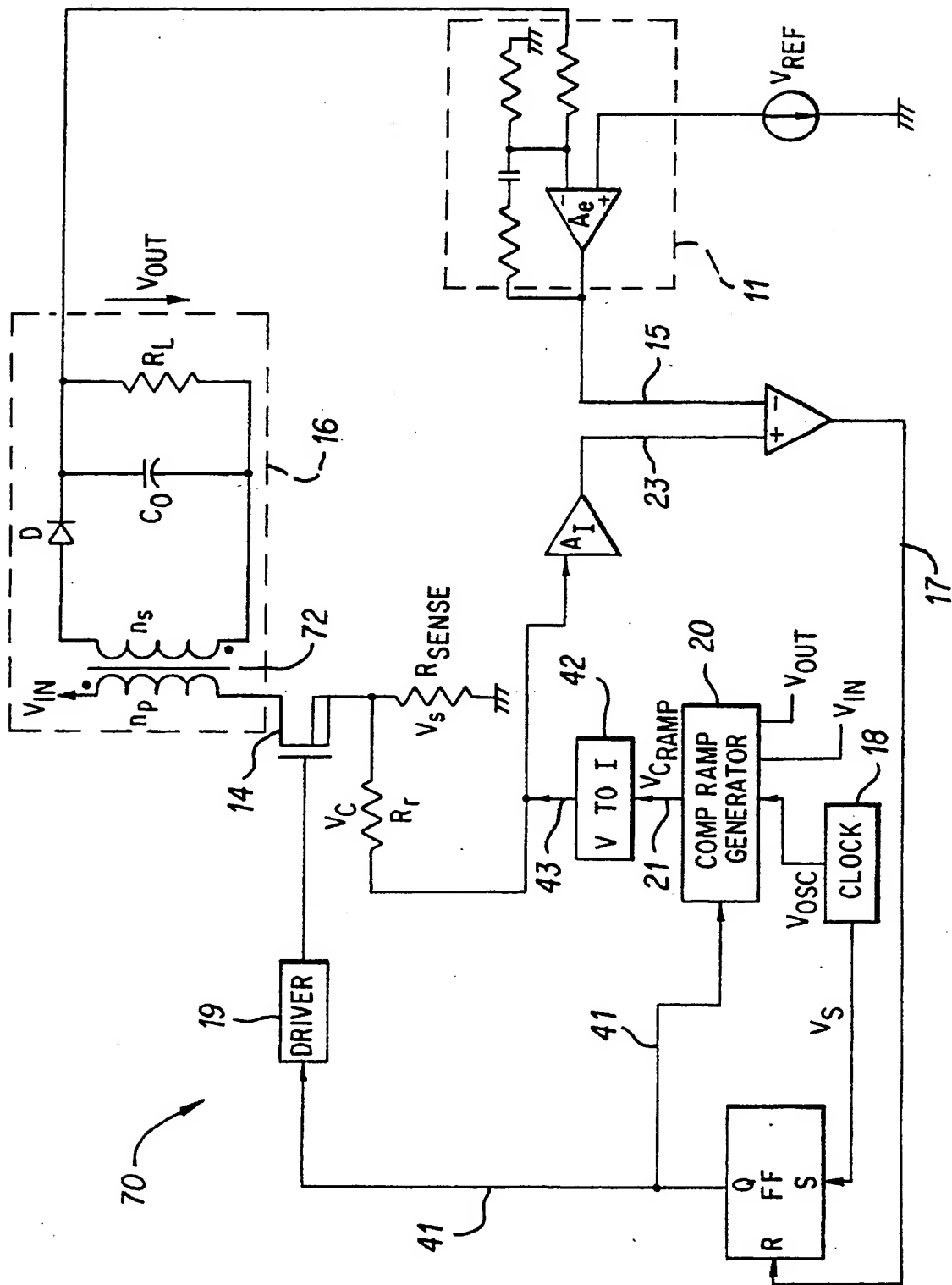


FIG. 7

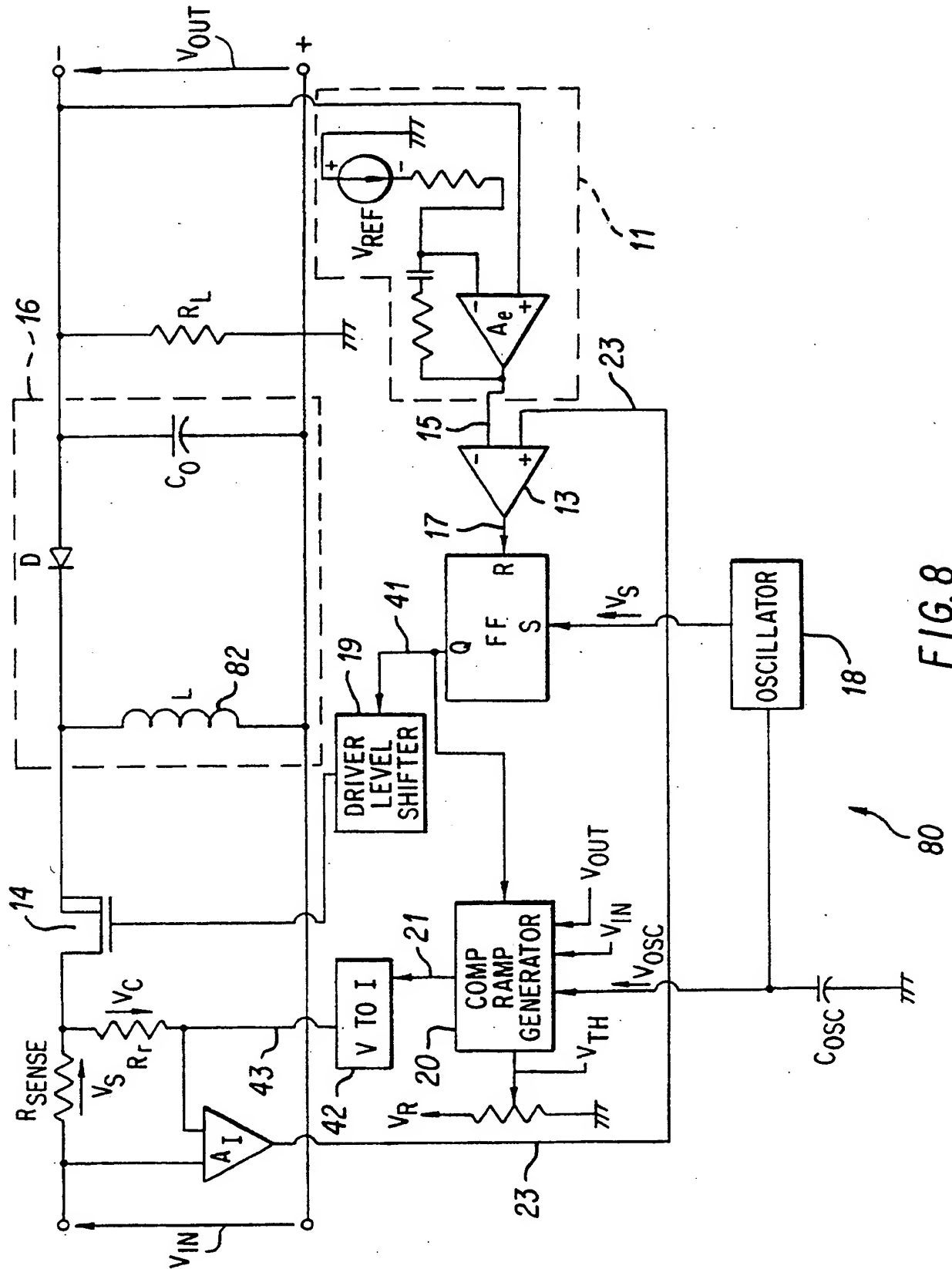
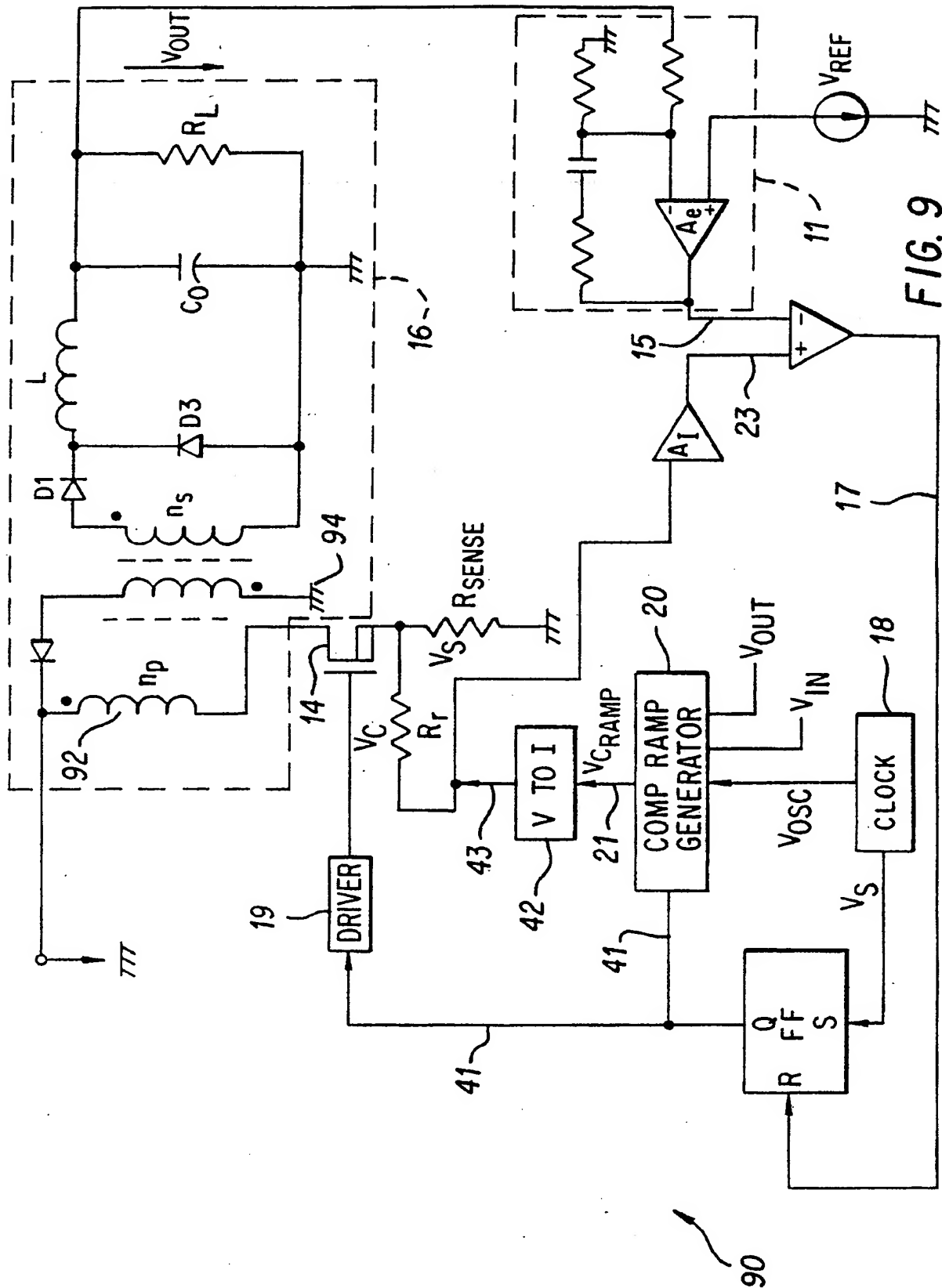


FIG. 8



(19)



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(54) Adaptive compensating ramp generator for current-mode DC/DC converters.

(57) A circuit (20, 40, 50, 60) for generating an optimal compensating ramp voltage signal V_{cramp} , with the minimum necessary slope, m_c , for a current mode DC/DC converter is shown. The adaptive compensating ramp generating circuit (20) is comprised of two voltage dividers (22, 24), the first voltage divider 22 divides an input voltage V_{IN} and the second voltage divider 24 divides an output voltage V_{OUT} . The first voltage divider (22) has two resistors (26, 28) in series: the first resistor (26) has a resistance of $(1/B - 1) \cdot R$ ohms and the second resistor (28) has a resistance of R ohms. V_{OUT} is divided by the second voltage divider (24) having two resistors (29, 30) in series: the first resistor (29) has a resistance of $(1/A - 1) \cdot R$ ohms and the second resistor (30) has a resistance of R ohms. The constants A , B , and C are selected for the particular type of DC/DC converter employed. The divided voltages $A \cdot V_{\text{OUT}}$ and $B \cdot V_{\text{IN}}$ are input into a voltage controlled current source (32). The voltage controlled current source (32) has a scaling resistor R_{scale} , an amplifier (36), a transistor Q , and a diode $D1$. The output of the current source (38) is coupled to a capacitor C_{ramp} whose voltage realizes the slope of the compensating ramp signal, V_{cramp} . The capacitor C_{ramp} is charged through R_{scale} .

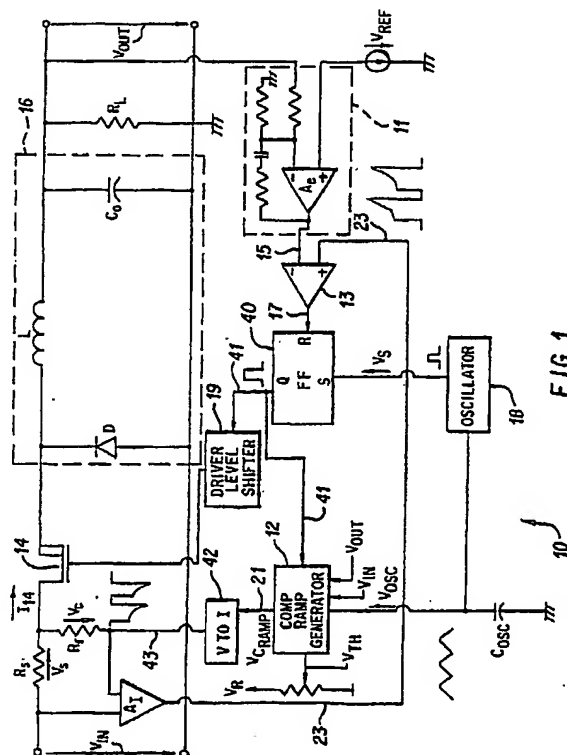


FIG. 1



European Patent
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EUROPEAN SEARCH REPORT

Application Number

EP 90 11 6028

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
P,X	EP-A-0 369 118 (ANT NACHRICHTENTECHNIK) * Abstract; page 2, line 45 - page 3, line 6; figure *	1,2,4, 12,14, 20,31, 33	H 02 M 3/156
A	WO-A-8 903 609 (ASTEC) * Abstract; page 5, line 30 - page 6, line 16; page 10, line 24 - page 11, line 8; page 16, lines 23-28; figures 2,4 *	1-19	
A	US-A-4 672 518 (MURDOCK) * Abstract; column 1, lines 34-44; column 3, lines 30-37; figure 2 *	1-19	
A	US-A-4 674 020 (HILL) * Abstract; column 4, lines 9-14; figure 3 *	1-19	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			H 02 M
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 12-04-1991	Examiner GENTILI L.
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